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OBSERVATION OF QUASI-CONTINUUM LINE EMISSION FROM Fe VII TO Fe X IN THE EXTREME-ULTRAVIOLET REGION BELOW 140 Å

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ABSTRACT

The line emission of Fe VII–Fe X ions in the extreme-ultraviolet region below 140 Å was measured in controlled laboratory experiments under conditions representative of stellar coronae. The observations are compared with predictions from standard spectral models using the CHIANTI and MEKAL atomic databases. We find that the atomic databases miss most of the line flux in this region. While some of the missing lines form isolated features, most add up to form a quasi continuum in the 60–120 Å region. This incompleteness can explain the poor fit when applying global-fitting techniques to spectra from cool stars measured by the *Extreme-Ultraviolet Explorer* satellite, the origin of which has been a source of controversy since the original observations were made.

Subject headings: atomic data — stars: coronae — Sun: corona — ultraviolet: stars

1. INTRODUCTION

Spectral line emission in the extreme-ultraviolet region provides a unique diagnostic opportunity for determining densities, elemental abundances, and, most importantly, the temperature structure of stellar coronae. In fact, EUV spectra can be reduced in order to yield the differential emission measure (DEM) distribution over a wide range of temperature and in order to give information related to the temperature structure of stellar coronae, which is fundamental to understanding the energy balance and heating mechanisms in stars. The EUV wavelength band was opened to stellar astrophysicists for high-resolution exploration with the launch of the *Extreme-Ultraviolet Explorer* (*EUVE*) in 1992. Additional high-resolution data are expected from the upcoming *Chandra X-Ray Observatory* mission. Its low-energy transmission grating spectrometer (LETGS) will provide high-resolution spectra in the EUV region below 140 Å.

EUVE has returned a plethora of superb spectra providing new insights into stellar atmospheres. Analysis techniques have focused on individual line emission with reliable flux measures and on global-fitting procedures averaging over the entire spectral range of information (Dupree et al. 1993; Schrijver et al. 1995). Global-fitting procedures, which in principle should provide a robust answer even in cases where no strong lines can be discerned, have been problematic in many instances. In particular, short-wavelength (SW) band spectra (70–180 Å) cannot be fitted properly without making controversial assumptions, as illustrated by the spectrum of the G-K binary α Centauri. This spectrum appears to have a low line-to-continuum ratio. The spectrum was fitted by Mewe et al. (1995b) with the widely used spectral analysis computer code SPEX. The code is based on a theoretical model for spectra emitted by hot, optically thin plasmas. Isothermal equilibrium spectra were calculated using the MEKAL atomic database described by Kaastra & Mewe (1993) and Mewe, Kaastra, & Liedahl (1995a). The best fit to the data required the presence of a high-temperature tail on the DEM with a temperature $\geq 30 \times 10^6$ K in order to fit what Mewe et al. (1995b) call the "featureless continuum." This tail is inconsistent with fits of *ROSAT* spectra at higher energies (Schmitt, Drake, & Stern 1996). Possible resolutions of this problem, such as metal abundances well below solar photospheric values or resonance scattering of the emission lines, have been discounted by subsequent analyses (Schmitt et al. 1996; Brickhouse 1996; Drake, Laming, & Widing 1997), and the argument was advanced that the atomic models are incomplete.

The statement that the models are incomplete seems at first surprising given the fact that the spectral models currently in use have aimed for a certain level of completeness. The MEKAL database used by Mewe et al. to fit the α Cen spectrum included lines identified in solar measurements (e.g., Behring et al. 1976; Doschek & Cowan 1984; Thomas & Neupert 1994), and, as such, it incorporates a virtually complete set of known lines in the EUV given by solar- and laboratory-based spectral compilations. A second set of lines for modeling stellar emission spectra is provided by the CHIANTI atomic database (Dere et al. 1997). Unlike the mostly semiempirical MEKAL database, the CHIANTI database represents a compilation of atomic parameters derived from calculations. This database was used to derive the DEM of the quiet Sun (Warren, Mariska, & Lean 1998) and was claimed to be "essentially complete for specifying the emission spectrum at wavelengths greater than 50 Å" (Dere et al. 1997). A similar data set is given by the Arcetri Spectral Code (Landini & Monsignori Fossi 1990). In addition, a spectrum model focusing solely on the iron EUV emission was developed by Brickhouse, Raymond, & Smith (1995). However, it was pointed out by Jordan (1996) that transitions from the intermediate-ionization states of iron of the type $3s3p^n4s \rightarrow 3s3p^{n+1}$, for example, which would fall in the band below 120 Å, are missing from the models. Because these types of transitions in other ions are known to be important contributors to the spectra, the analysis codes must be incomplete.

To resolve the question of the existence of significant spectral flux from lines missing in global analysis codes, we have performed a series of controlled laboratory measurements of the line emission from iron in the 60–140 Å wavelength band. Our measurements concentrated on the emission from Fe VII, Fe VIII, Fe IX, and Fe X, which are important for emission from plasmas near 10^6 K and below. Thus, our results are important

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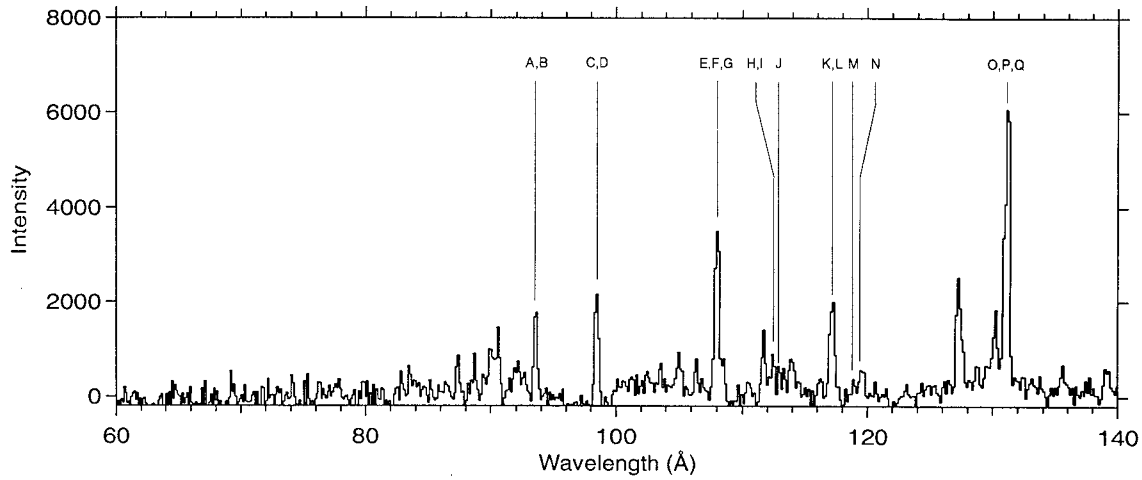

FIG. 1.—Line emission spectrum of Fe VII and Fe VIII excited at a beam energy of 140 eV. The data are adjusted for instrumental efficiency. Fe VIII features correlated with the MEKAL database are labeled with uppercase letters. Unlabeled features are not in the database.

for cool stars like α Cen on Procyon and, to a lesser extent, for hotter stars like Capella or UX Ari.

2. SPECTROSCOPIC FACILITY

The measurements were carried out using the spectroscopic capabilities at the Livermore electron beam ion trap (EBIT) facility. The EBIT is a modified electron beam ion source built to study spectroscopically the interaction of highly charged ions with an electron beam by looking directly into the trap. The device has been routinely used for laboratory astrophysics measurements in the X-ray region (e.g., Savin et al. 1996; Decaux et al. 1997; Brown et al. 1998). The implementation of a flat-field spectrometer utilizing a variable line spacing grating (average 1200 lines mm^{-1}) with a focal distance of 27 cm has extended the spectral capabilities to the EUV region (Beiersdorfer et al. 1999). The spectrometer utilizes a 1 inch square, thinned, back-illuminated, LN_2-cooled CCD camera (1024 × 1024 pixels) to detect the dispersed photons. We use the CCD in the charge integration mode. The resolution of our spectrometer is about 0.3 Å at 100 Å. The grating is blazed near 100 Å, and higher order reflections are readily seen. In the following, we discuss only lines measured in first order.

The electron density for the present experiments is about 5×10^{11} cm^{-3}, i.e., comparable to the density found in stellar coronae, and spectra are unaffected by opacity effects. By setting the electron beam to a particular energy, it is possible to select the charge state of interest for spectroscopic study. Frequent filling and dumping of the trap with iron minimizes the presence of impurity ions so that pure iron spectra can be recorded. Background light levels are accounted for by subtracting spectra with and without iron in the trap.

3. RESULTS

The ionization potential of Fe VII is about 122 eV, and that of Fe VIII is about 149 eV. This means that no ionization state higher than Fe VIII will be produced in our spectroscopic source if we set the electron beam energy to less than 149 eV. A spectrum obtained with the electron beam energy set to 140 eV is shown in Figure 1. The spectrum shows a set of well-resolved features. The strongest feature, situated at 131 Å, originates from a blend of three $3d$–$4f$ transitions in Fe VIII. Most other features are also from transitions in Fe VIII. We have identified the group of lines situated near 117 Å as $3d$–$6f$ transitions that originate from Fe VII. Since the ionization potential of Fe VII corresponds to a series limit wavelength of 102 Å, we do not expect to see any Fe VII lines with wavelengths less than this value. Since no Fe IX is produced at this beam energy, all lines seen below this wavelength threshold must be from Fe VIII ions.

The observed lines are compared with data in the MEKAL database, which, as our discussion below shows, is the most complete database for the region of interest. Lines belonging to Fe VIII and found in the MEKAL database are labeled with uppercase letters in Figure 1. The comparison shows that most strong lines are represented by the 17 lines in the MEKAL database. Exceptions are the lines at 127 and 130 Å. These are likely to originate from $3d$–$5f$ transitions in Fe VII ions. Weaker features near the Fe VIII series limit at ≥83 Å, which we attribute to $3d$–nf ($n \geq 8$), are also missing from the databases.

In Figure 2, we show a spectrum recorded at a beam energy of 200 eV. Because the ionization potential of Fe IX is 233 eV, no Fe X is produced. Comparing Figures 1 and 2, we find several new lines in the spectrum that originate from Fe IX ions. Comparing our spectrum with the MEKAL database, we can correlate all six Fe IX lines in that database with observed features. The Fe IX lines found in MEKAL are labeled by Arabic numerals.

The spectrum in Figure 2 shows several moderately intense lines missing from the models, i.e., the lines at 90 and 92 Å and the unresolved set of lines at 114 Å. More importantly, however, we note that the spectral flux between the prominent lines deviates significantly from the zero. This elevated intensity is attributed to unresolved weak transitions in Fe IX, all of which are missing from the models. These weak lines add up to form a quasi continuum that would appear to enhance the bremsstrahlung and recombination continuum in plasma sources.

An even more dramatic enhancement of the “background” spectral intensity is seen in Figure 3. Here we plot the spectrum recorded at an electron beam energy of 250 eV. This energy is above the ionization potential of Fe IX and below the 263 eV ionization potential of Fe X. At this energy, we produce and excite Fe X ions in addition to the ions from the lower ionization states, while no Fe XI ions are produced. The 16 Fe X lines listed in MEKAL were correlated with features in

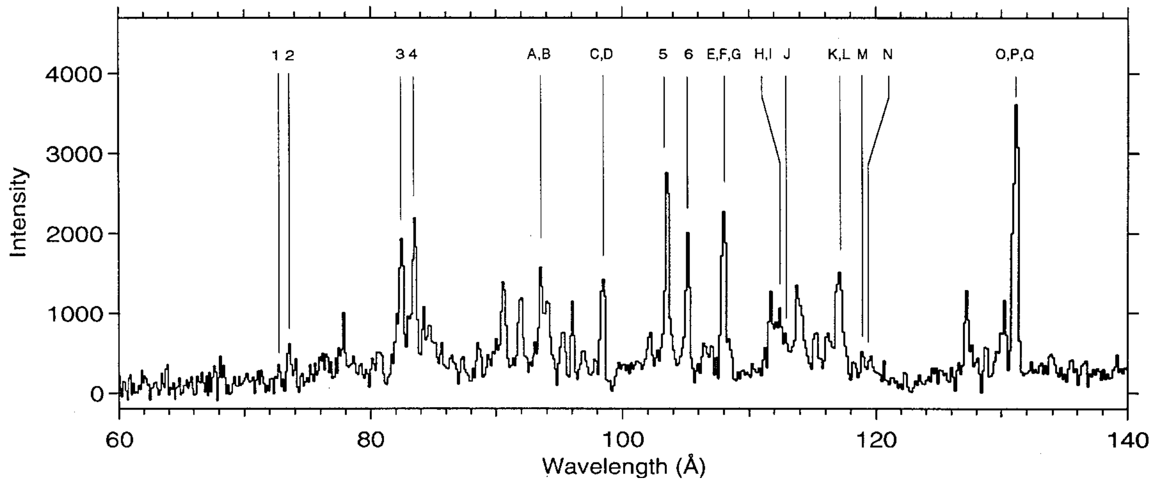

FIG. 2.—Line emission from Fe VII, Fe VIII, and Fe IX ions excited at a beam energy of 200 eV and adjusted for instrumental efficiency. Features that can be correlated with the MEKAL database are labeled with uppercase letters (Fe VIII) and Arabic numerals (Fe IX). Unlabeled features are not in the database.

our observations and denoted with lowercase letters. The strongest lines are from $3p$–$4s$ transitions; these are denoted by lowercase letters i through p. The majority of the Fe X contribution to the spectrum comes from weak lines that, together with weak lines from Fe IX, form a significant quasi continuum. In fact, the spectral intensity never dips to a vanishing level.

4. DISCUSSION

The spectral modeling codes predict only a small subset of the lines observed in a coronal-density, opacity-free laboratory source. To illustrate this, we show in Figure 4 the predictions from the MEKAL model. Here we display all Fe VIII, Fe IX, and Fe X lines included in the model. The lines were convolved with a 0.2 Å FWHM Gaussian line profile, and the relative abundance ratios of each ionization state were adjusted to match the intensity of the strongest lines in the experimental spectrum shown in Figure 3. As mentioned, the model misses several prominent lines and completely fails to predict the quasi continuum formed by an unresolved mass of weak lines. In fact, the model accounts for less than 40% of the flux in Figure 1 and less than 31% of the flux in Figures 2 and 3. A comparison with predictions from other databases is not shown. MEKAL includes a total of 39 lines in the region of interest; the Arcetri Spectral Code contains 10 lines; the Brickhouse-Raymond-Smith model has none. CHIANTI, which was claimed to be "essentially complete," lists 19 lines but gives intensities for only six lines, and thus it is of little use in the analysis of iron spectra in this wavelength band.

The reason that so few iron lines of the type $3l$–nl' with $n \geq 4$ are included in the atomic models is that these lines are thought to be weak and insignificant. However, the Fe IX lines labeled 3–6 in Figure 3 were discerned in the SW spectrum of α Cen (Mewe et al. 1995b), as were the Fe X lines labeled i–n. These lines provided significant contributions to the overall flux and were fitted with intensities not much smaller than Mg VIII or Ne VIII lines. As Figure 3 illustrates, the missing lines contribute flux that increases the level included in the models by more than a factor of 3. They must therefore play a significant role, and a global fit without including this flux

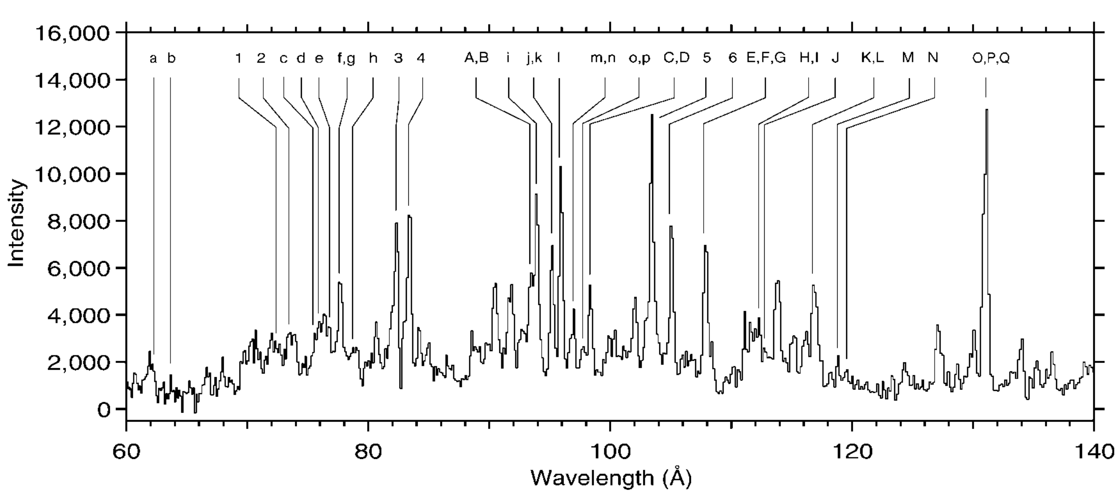

FIG. 3.—Line emission from Fe VII, Fe VIII, Fe IX, and Fe X ions excited at a beam energy of 250 eV and adjusted for instrumental efficiency. Features correlated with the MEKAL database are labeled with uppercase letters (Fe VIII), Arabic numerals (Fe IX), and lowercase letters (Fe X). Unlabeled features are not in the database. A significant amount of the observed flux is in a quasi continuum formed by unresolved lines.

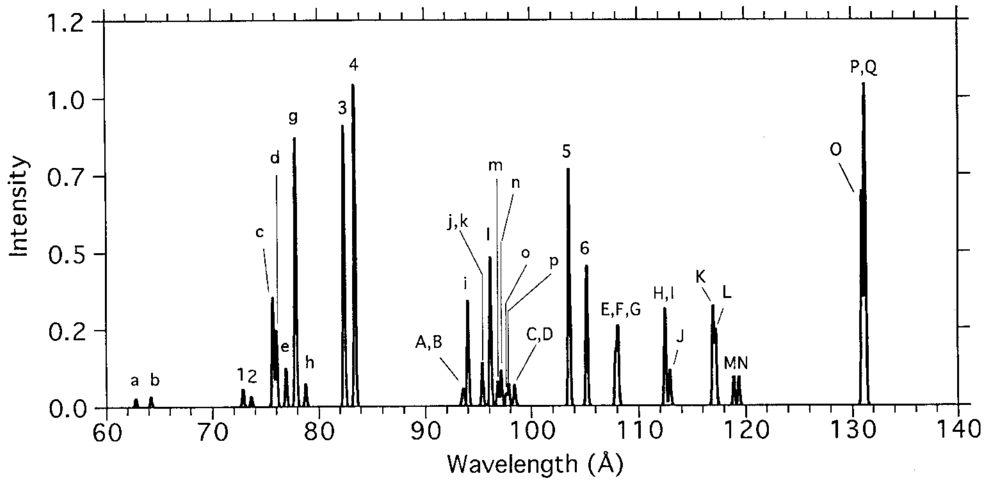

FIG. 4.—Simulated line emission using the MEKAL database. Features are labeled in the same notation used in Figs. 1–3. The relative ion abundances have been adjusted to simulate the experimental spectrum in Fig. 3.

cannot produce reliable results. The contention that the continuum in the SW spectra of cool stars could be caused by unresolved lines not in the spectral analysis models thus seems highly plausible.

We have extended our measurements only as high as Fe X. The higher ionization states of iron will certainly add further to the quasi continuum, as already suggested by Jordan (1996). Measurements are in progress to determine the contributions from these ionization states (Beiersdorfer et al. 1999). The high density of lines in this region from many iron charge states may make it difficult to resolve most of the weak lines, even with better resolving power than in the present experiment or with the resolving power afforded by LETGS on the *Chandra X-Ray Observatory*. A complete accounting of these lines in the spectral modeling codes is therefore essential even when measurements are made with high-resolution instruments.

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